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Do gamma-ray burst sources repeat?

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ABSTRACT

Following the discovery by Quashnock & Lamb of an apparent excess of γ-ray burst pairs with small angular separations, we reanalyse the angular distribution of the bursts in the BATSE catalogue. We find that, in addition to an excess of close pairs, there is also a comparable excess of antipodal bursts, i.e. pairs of bursts separated by about 180° in the sky. Both excesses are moderately significant. Quashnock & Lamb argue that the excess of burst pairs with small angular separations is evidence that many bursts repeat, but obviously this hypothesis cannot explain the excess of antipodal coincidences. Since the two excesses have similar characteristics, and since we cannot think of any physical model of bursts that can produce antipodal pairs, we suggest that both excesses may be due to some unknown selection effect.

Key words: gamma-rays: bursts.

1 INTRODUCTION

In a Letter in this issue, Quashnock & Lamb (1993, hereafter QL) analyse the distribution of angular separations of bursts in the publicly available BATSE catalogue of gamma-ray bursts. They find a significant excess of close pairs of bursts with angular separations smaller than $\sim 4°$, compared to the number of such pairs expected for a random distribution of positions on the sky. On this basis they suggest that γ-ray bursts repeat. In their hypothesis, the close pairs actually arise from the same source, but they are assigned slightly different positions because of measurement errors, which are typically about 4° or larger. If QL are correct then many extragalactic models may be ruled out; in particular, the neutron star merger model (Eichler et al. 1989; Narayan, Paczyński & Piran 1992) would become rather unlikely. Furthermore, as QL argue, their result implies a close relationship between classical γ-ray bursts and the three known soft γ-ray repeaters. Since the latter are known to be located close to or in the Galaxy, this would give further support to the suggestion that the classical burst sources are also located in the Galaxy. In view of the importance of these conclusions, we reanalyse in this Letter the angular distribution of gamma-ray bursts.

We repeat here the nearest neighbour analysis employed by QL, and add to it another analysis based on the more standard angular autocorrelation function. We find that, while there does appear to be an excess of close pairs of bursts with angular separations less than 4°, as claimed by QL, there is also an equivalent excess of antipodal pairs of bursts with angular separations larger than 176°. QL explain the excess of nearby bursts as signals from repeating sources, but we cannot think of any physical model to explain the excess of antipodal bursts. Considering the similarity of the two effects, we conclude that both effects, if real, are probably due to some unknown selection effect.

In Section 2 of this Letter we analyse the data. We examine the correlation function of the full sample of 260 bursts in the BATSE catalogue in Section 2.1, and we present the nearest and farthest neighbour analysis for this sample in Section 2.2. QL do not use the full sample, but analyse a subsample defined by the availability of counts in both the 64-ms and 1024-ms channels on BATSE. Another subset could be defined by including only those bursts for which the formal positional accuracy is better than 4°. We discuss results from these subsamples in Section 2.3. We conclude in Section 3 with a discussion of the implications of the results.

2 ANALYSIS

2.1 The two-point angular correlation function

A data set composed of randomly positioned sources, some of which repeat, has a simple angular correlation function: a delta-function peak at the origin due to the repeaters, and a slightly negative constant elsewhere. Errors in position measurements will spread out the delta function to a broadened peak at the origin, with a width and shape determined by the probability distribution of the positional errors, but nowhere else other than at the origin do we expect any significant peak or dip. This simple structure of

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the two-point correlation function suggests that it should be a clean statistic with which to test the repeating source hypothesis.

The correlation function of all the 260 bursts in the BATSE catalogue is shown in Fig. 1(a). As expected from the QL analysis, there is a peak in the bin corresponding to $\theta < 4°$. To assess the statistical significance of this peak, we have carried out Monte Carlo simulations with 10 000 random samples. From this we estimate that the peak has an amplitude of 1.75 standard deviations (1.75σ), and that the probability of obtaining by chance a peak as strong as or stronger than the observed one is 0.0957 (9.57 per cent). These results are given in Table 1, along with the results of various other calculations discussed later in the paper. Note that the probability distribution of the values of the correlation function is not Gaussian. Here and elsewhere in the text, therefore, all significance levels that we quote are obtained from Monte Carlo simulations. Note also that a small probability in Table 1 means that it is unlikely that the particular event could have happened by chance, and therefore implies high significance.

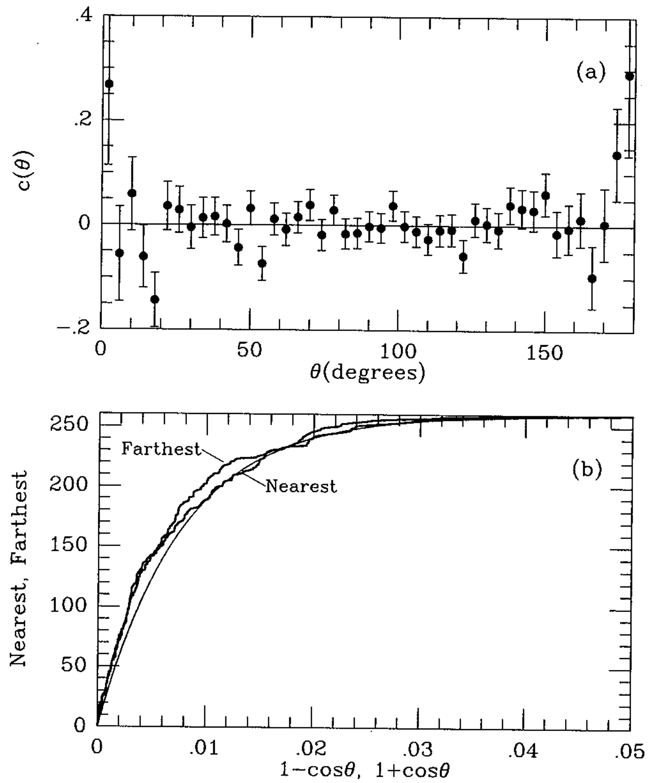

Figure 1. (a) The angular autocorrelation function of the full sample of 260 bursts in the BATSE catalogue, represented in 4° bins. The error bars correspond to one standard deviation as estimated through Monte Carlo simulations. Note that the antipodal peak near $\theta \sim 180°$ is somewhat higher and wider than the direct peak near $\theta \sim 0°$. There are marginally significant negative dips adjacent to both peaks, and it is plausible that the excess counts in the peaks are supplied by the lack of bursts in the dips. (b) The cumulative numbers of nearest neighbours closer than θ as a function of $1-\cos\theta$, and farthest neighbours more distant than θ as a function of $1+\cos\theta$, both shown as thick lines. The theoretically expected curve for a random sample is shown by the smooth thin line. Note that the excess extends to larger angles in the case of farthest neighbours, whereas the KS statistic (i.e. the largest distance between the observed and theoretical curves) is slightly higher in the case of nearest neighbours.

While the existence of a peak at $\theta < 4°$ agrees with the QL result, there is another unexpected peak at the antipode, corresponding to the bin with $\theta > 176°$. The second peak is slightly wider than the peak at the origin and has an amplitude of 1.86σ, which is marginally more significant (probability = 0.0724) than the direct peak. In fact, while the statistical significance of each of the single peaks is only moderate, the statistical significance of having *both* peaks is much higher. Additionally, there are weak negative excursions in the correlation function at about $\theta \sim 10°$–$20°$ and $\theta \sim 160°$–$170°$ which appear to be marginally significant. We do not discuss these in detail, but merely note that, if real, their presence might indicate that the *shape* of the correlation function is not consistent with the repeater model.

2.2 Nearest neighbour analysis

Quashnock & Lamb do not employ the correlation function, but instead use a 'nearest neighbour statistic'. According to this statistic, they measure for each burst in the catalogue the angular distance to its nearest neighbour, and compute the cumulative distribution of this quantity for the observed sample. They then compare this cumulative with the distribution expected for a random sample. In Fig. 1(b) we present this comparison for the full sample of 260 bursts. We show the number of bursts with nearest neighbours closer than an angle θ as a function of $1-\cos\theta$. As expected from QL's analysis and from the correlation function approach discussed in Section 2.1, there is evidence for an excess of nearby bursts. Motivated by our discovery of the antipodal peak in the correlation function, we also calculate for each burst the distance to its *farthest* neighbour, that is, the burst that is nearest to the antipodal point. We plot this cumulative distribution in Fig. 1(b), where now the x-axis is $1+\cos\theta$ and the vertical axis represents the number of bursts with farthest neighbour more distant than angle θ. As expected from the correlation function, we find that there is again an excess of antipodal bursts compared to the distribution expected for random bursts. Visually at least, we would say that the evidence for an excess is about equally strong for nearest and farthest neighbours.

Table 1. Correlation functions and significance levels.

Sample	Number	$c(\leq 4°)$	Prob	$c(\geq 176°)$	Prob
Full Sample	260	$0.268 = 1.75\sigma$	0.096	$0.292 = 1.86\sigma$	0.072
QL Sample	201	$0.389 = 1.95\sigma$	0.052	$0.348 = 1.74\sigma$	0.082
Full, $\Delta\theta_P \leq 4°$	131	$0.254 = 0.84\sigma$	0.423	$0.832 = 2.69\sigma$	0.010
QL, $\Delta\theta_P \leq 4°$	108	$0.279 = 0.74\sigma$	0.575	$0.989 = 2.60\sigma$	0.016

What is the significance of these deviations? Since Fig. 1(b) is a cumulative distribution, one might consider using the Kolmogorov–Smirnov (KS) test to estimate the significance. In this method one measures the KS distance, which is the maximum distance between the observed cumulative curve and the theoretically expected curve. One then calculates the probability of obtaining a distance at least as large as the observed one by the standard KS method (e.g. Press et al. 1992). The KS method, however, assumes that all the data points are independent, but this is not the case in the present distribution because the set of nearest neighbour distances can have strong correlations. To see this, consider the case when two bursts happen to lie very close to each other on the sky. Both bursts will yield the same small nearest neighbour distance, and therefore this distance will be counted twice. This demonstrates that a direct application of the KS method is invalid.

To measure correctly the statistical significance of the deviations, we have generated 10 000 random data sets and calculated the distribution of the KS distance. We find that the probabilities of obtaining KS distances greater than those observed in the 260-burst BATSE sample are 0.012 for the nearest neighbours and 0.11 for the farthest neighbours. (Note that the standard KS test gives probabilities of 0.0016 and 0.019, showing that the KS test, by neglecting the effect of correlations, leads to unduly optimistic estimates of the significance.) The results are moderately significant. If we estimate the probability for both nearest and farthest neighbours to have such large deviations simultaneously, we find that it is 0.0019, which is more highly significant. Therefore once again we reach the same conclusion as we did from the correlation analysis in Section 2.1: namely, while we find an excess of nearest and farthest neighbours in the data, these excesses are only moderately significant. However, the probability of obtaining both excesses simultaneously by chance is very small, and therefore the evidence for such a signal is more significant.

2.3 Subsamples of the BATSE catalogue

The basic variables in our analysis are the positions of the bursts. As stated in the instructions with the BATSE catalogue, burst positions have variable errors depending on the strengths of the bursts, the position and orientation of the *Compton GRO* satellite, and other parameters. The BATSE catalogue gives an estimate of the formal positional error $\Delta\theta_{\rm P}$ for each burst due to Poissonian fluctuations in the observed γ-ray counts, to which an additional systematic error of 4° should be added in quadrature[1] to yield the total positional error, $\Delta\theta_{\rm tot}=[\Delta\theta_{\rm P}^2+(4°)^2]^{1/2}$. In some cases the estimated $\Delta\theta_{\rm P}$ is quite large (up to 20°), and it is reasonable to exclude such bursts from the samples. Since we are looking for correlations on angular separations $\sim 4°$, it is clearly meaningless to argue that a burst with a positional error of, say, 10° is within 4° from another burst. We have therefore repeated our analysis with a subsample of bursts for which the quoted formal $\Delta\theta_{\rm P}$ values are 4° or less (i.e. $\Delta\theta_{\rm tot}\leq 5\overset{\circ}{.}7$). This reduces the sample from 260 bursts to 131 bursts. When we analyse this sample, the correlation analysis gives a modest peak of 0.84σ for $\theta<4°$, and an impressive peak of 2.69σ for antipodal neighbours between 176° and 180°. The corresponding probabilities for chance occurrence are 0.42 for the direct peak and 0.010 for the antipodal peak (see Table 1). Similarly, the QL statistic based on the KS distance gives excesses of 0.83σ and 1.61σ for nearest and farthest neighbours, corresponding to chance probabilities of 0.47 and 0.027. The fact that the statistical significance of the nearest neighbour excess does not increase, but in fact *decreases*, when we throw away the bursts with large positional errors supports our suspicion that the observed anomaly may not be due to a real physical effect. Furthermore, the peak is very narrow compared to the typical positional errors in the BATSE catalogue. This shows that the shape of the nearest neighbour peak is not consistent with the errors in the positions of the bursts, an argument that has been given in more detail by Hartmann et al. (1993).

For completeness, we have also repeated the analysis with the particular subsample used by QL. They divide the data into subgroups according to the γ-ray counts measured in the 64- and 1024-ms channels. Their total sample, identified as types I and II in their paper, consists of 201 bursts; we refer to this as the QL sample. Among all the subsamples that QL analyse, they find the strongest signal in this particular combined sample. Using 10 000 Monte Carlo simulations with synthetic data, we find that there is a probability of 0.0015 of obtaining by chance a nearest neighbour deviation comparable to the signal observed in the QL sample. We also find a modest excess of farthest neighbours in this sample, with a Monte Carlo probability of 0.36. The corresponding peaks in the correlation function represent deviations at the levels of 1.95σ and 1.74σ respectively (Table 1).

Our final subset is a truncated QL sample of 108 bursts, where we take the QL sample and eliminate all bursts with $\Delta\theta_{\rm P}>4°$. The hypothesis of repeating bursts put forward by QL suggests that, by eliminating bursts with highly uncertain positions, the statistical significance of the effect should increase. We find this not to be the case. The angular correlation function for this data set is shown in Fig. 2(a). We see both the forward and antipodal peaks, but the forward peak represents only a 0.74σ deviation while the antipodal peak is at 2.60σ (see Table 1 for the corresponding probabilities). Similarly, we show in Fig. 2(b) the nearest/farthest statistic. Here we find that the KS distance for the distribution of nearest bursts is only 0.68σ (random chance probability 0.66), while for the farthest bursts the KS distance is 1.24σ, corresponding to a random chance probability of 0.10.

3 SUMMARY AND DISCUSSION

Our primary conclusions are the following.

(i) The BATSE data do contain some evidence for an excess of pairs of bursts with angular separations smaller than 4°. However, there is equally good evidence for an excess of nearly antipodal pairs, with separations between 176° and 180°. In fact, the two excesses are fairly similar both in amplitude and in shape. The nearest neighbour statistic of QL favours the nearest neighbour excess, while our correlation function analysis finds stronger evidence for the antipodal peak. Both peaks appear to be about 4° wide.

(ii) The individual statistical significances of the two excesses are moderate ($\gtrsim 2\sigma$, see Table 1), but, when we combine the excesses in the forward and antipodal directions

[1] $\Delta\theta_{\rm P}$, 4° and $\Delta\theta_{\rm tot}$ here correspond to $\theta_{\rm stat}$, $\theta_{\rm sys}$ and $\theta_{\rm err}$ in QL.

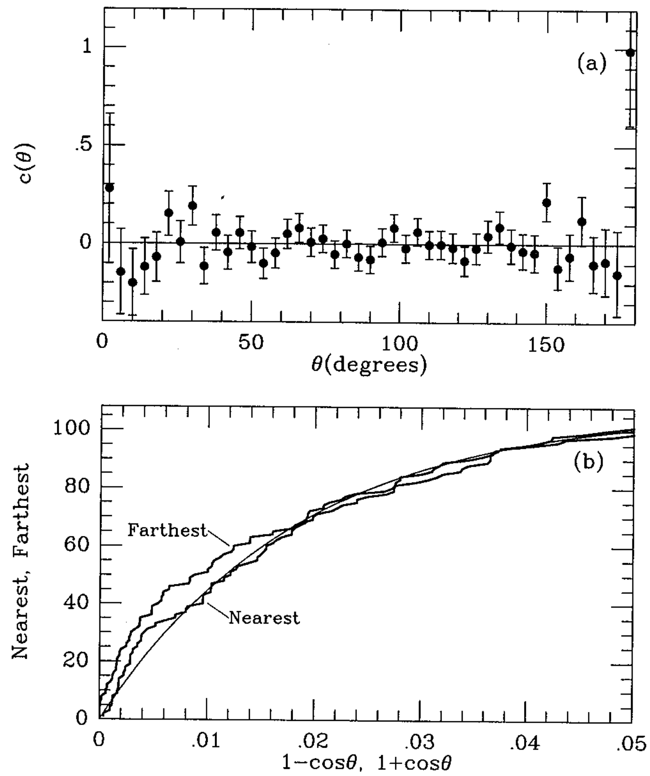

Figure 2. (a) The angular autocorrelation function of the 108 bursts out of the QL sample that have Poissonian positional errors $\Delta\theta_P \le 4°$. Note that the antipodal peak is much stronger than the direct peak, the latter being practically insignificant. (b) The cumulative numbers of nearest neighbours as a function of $1 - \cos\theta$ and farthest neighbours as a function of $1 + \cos\theta$, shown as thick lines. The theoretically expected curve is shown by the thin line. The nearest neighbour curve is very close to the expected curve, whereas the farthest neighbour curve shows an apparently significant deviation.

and compute the probability of obtaining both simultaneously, we find much higher significance. (Of course, there are obvious dangers in carefully selecting two hypotheses in this fashion and combining them.)

(iii) When we eliminate bursts with Poisson positional errors $\Delta\theta_P > 4°$ (which correspond to total errors $\Delta\theta_{tot} > 5.°7$), far from becoming stronger, the evidence for the excesses actually becomes weaker. In fact, the decrease in the signal is quite drastic in the case of nearest neighbour pairs, while it is more modest for the antipodal pairs. In other words, the evidence for an excess of close pairs is very volatile, depending on the particular sample chosen, while the excess of antipodal pairs shows a little more stability at least within the tests that we have done (Table 1). Note that bursts with large $\Delta\theta_P$ are generally weaker, and one could argue that by eliminating them we eliminate the repeating weak bursts (according to the QL model). The large positional error of the weak bursts, however, means that these bursts should not have shown any evidence for the repeater model in the first place. Thus, in general, we conclude that the shapes of the correlation function and the nearest/farthest statistic are inconsistent with the repeater model, given the positional errors of the bursts. This shape argument has been used by Hartmann et al. (1993) and others to argue against the QL model of repeaters.

The main new result in this paper is that there are actually two independent excesses in the angular correlation function of gamma-ray bursts: an excess of nearby neighbours within 4° (as discovered by QL), and an additional excess of farthest neighbours (> 176°). We have been unable to come up with any physical model that can explain an excess of bursts within 4° of the antipode. Obviously, a population of repeaters cannot produce this effect. An antipodal excess may occur if the bursts are located along a narrow line in space or in a very thin disc. Such distributions, however, are ruled out by the observed overall isotropy of the positions of the bursts (Meegan et al. 1992), and inhomogeneities in the BATSE sky coverage occur on much too wide an angular scale to produce features with a width of only 4°.

Considering the strong similarity of the two excesses, we think that one should seek a common explanation for the two peaks. Occam's Razor too would argue for a single effect. Since we have been unable to come up with any physical model that can produce the antipodal excess, we conclude that the excess of close pairs of bursts discovered by QL and the antipodal excess that we discuss here are both caused by some selection effect, unless they are due to an unusual statistical fluctuation. We do not have any specific idea as to the nature of the selection effect.

After we submitted this paper for publication, we became aware of papers by Hartmann et al. (1993, referred to above) and Nowak (1994) which discuss the shape of the angular correlation function of gamma-ray bursts in detail, and demonstrate that the data are not consistent with a repeater model. We also received a paper by Maoz (1994), in which the author has proposed a specific selection effect whereby the nearest neighbour and antipodal peaks in the correlation function may arise naturally.

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